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Noe

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(54) **ADJUSTABLE DIRECTIONAL COUPLER CIRCUIT**

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H01P 5/04 (2006.01)

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CPC .. ***H01P 5/18*** (2013.01); ***H01P 5/04*** (2013.01); ***H01P 5/184*** (2013.01)

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USPC 333/17.1, 109, 111
See application file for complete search history.

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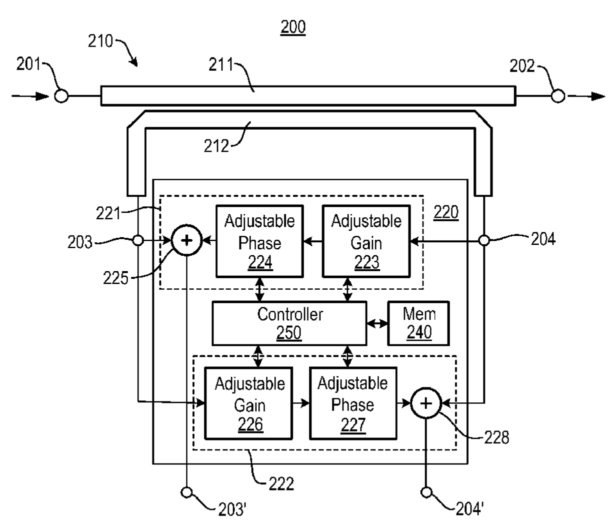
(57) **ABSTRACT**

An adjustable directional coupler circuit includes a directional coupler and a correction circuit. The directional coupler includes a first port for receiving an input signal; a second port for outputting the input signal to a load; a third port for outputting a first coupled signal including a desired first coupled signal proportional to forward power of the input signal and an extraneous first coupled signal proportional to reverse power of a reflected signal; and a fourth port for outputting a second coupled signal including a desired second coupled signal proportional to the reverse power and an extraneous second coupled signal proportional to the forward power. The correction circuit adjusts magnitude and phase of a sample of the second coupled signal to provide an adjusted second coupled signal, and to sum the adjusted second coupled signal and the first coupled signal to cancel the extraneous first coupled signal.

18 Claims, 6 Drawing Sheets



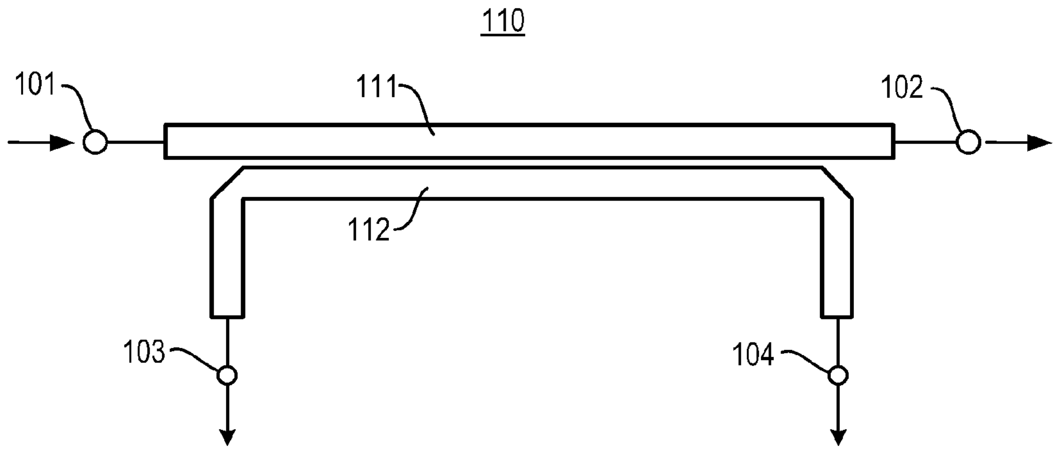

110
101
111
102
112
103
104

Fig. 1

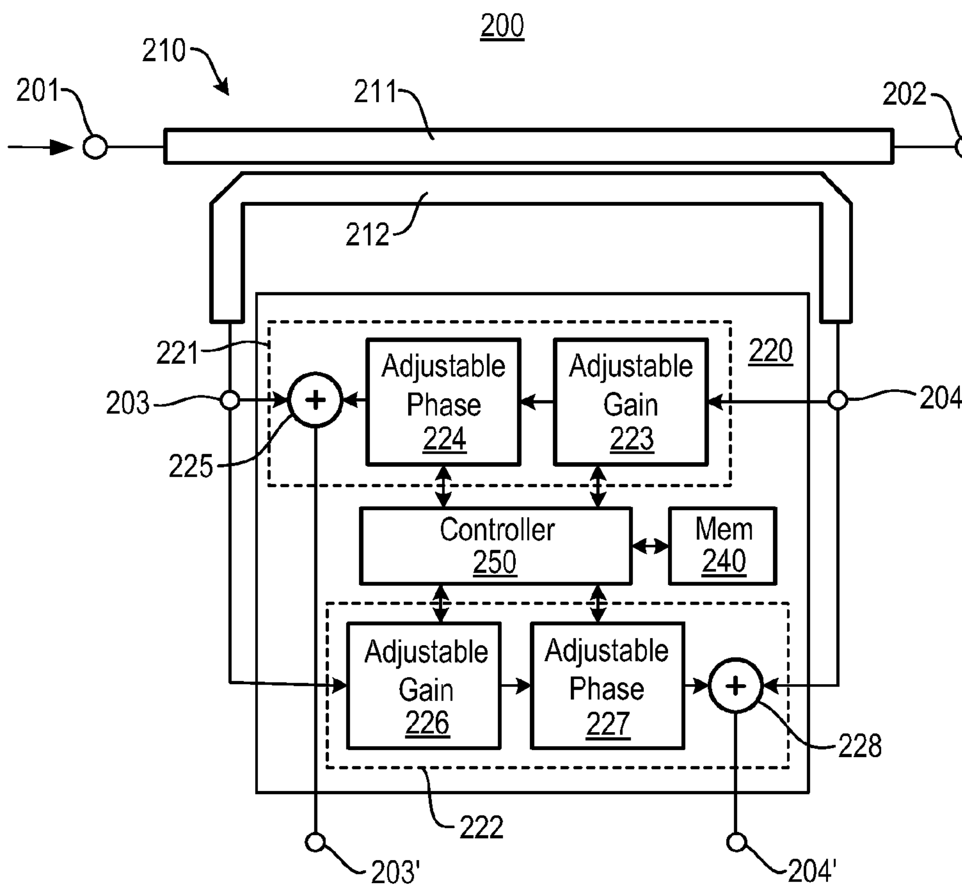

200
210
201
211
202
212
221
220
203
Adjustable Phase 224
Adjustable Gain 223
204
225
Controller 250
Mem 240
Adjustable Gain 226
Adjustable Phase 227
228
222
203'
204'

Fig. 2

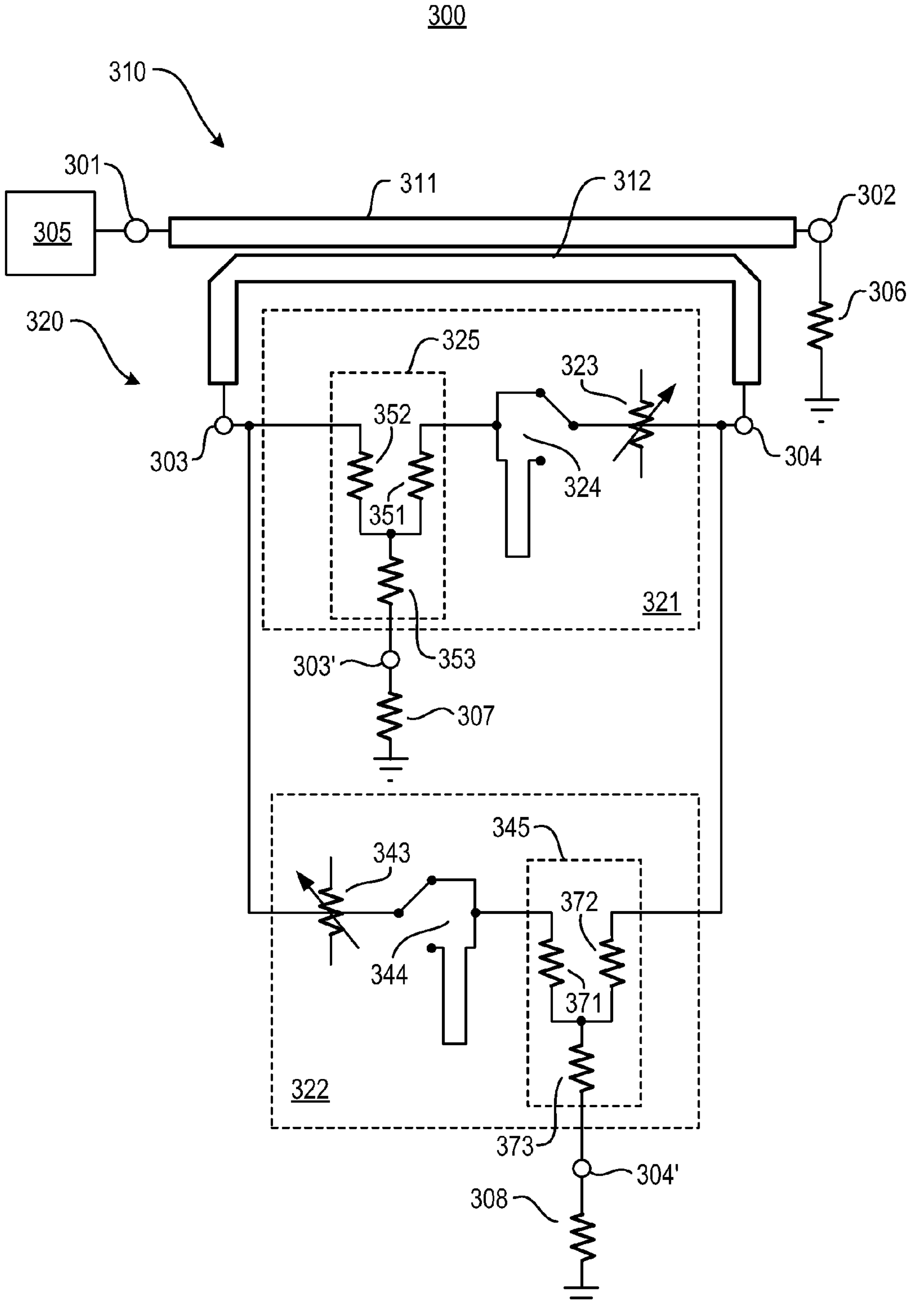

300
310
301
311
312
302
305
306
320
325
323
352
303
304
324
351
321
353
303'
307
345
343
372
344
371
322
373
304'
308

Fig. 3

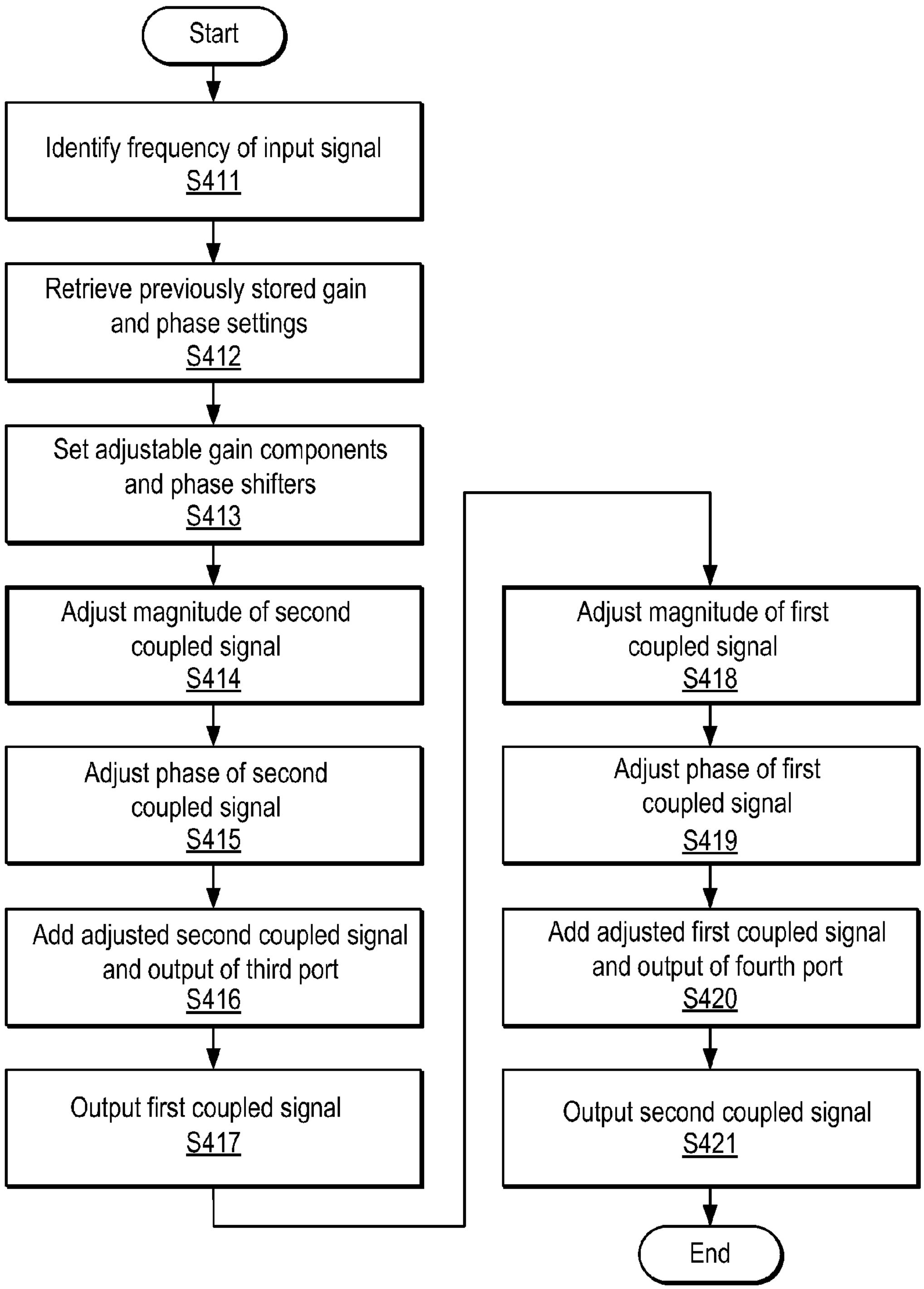
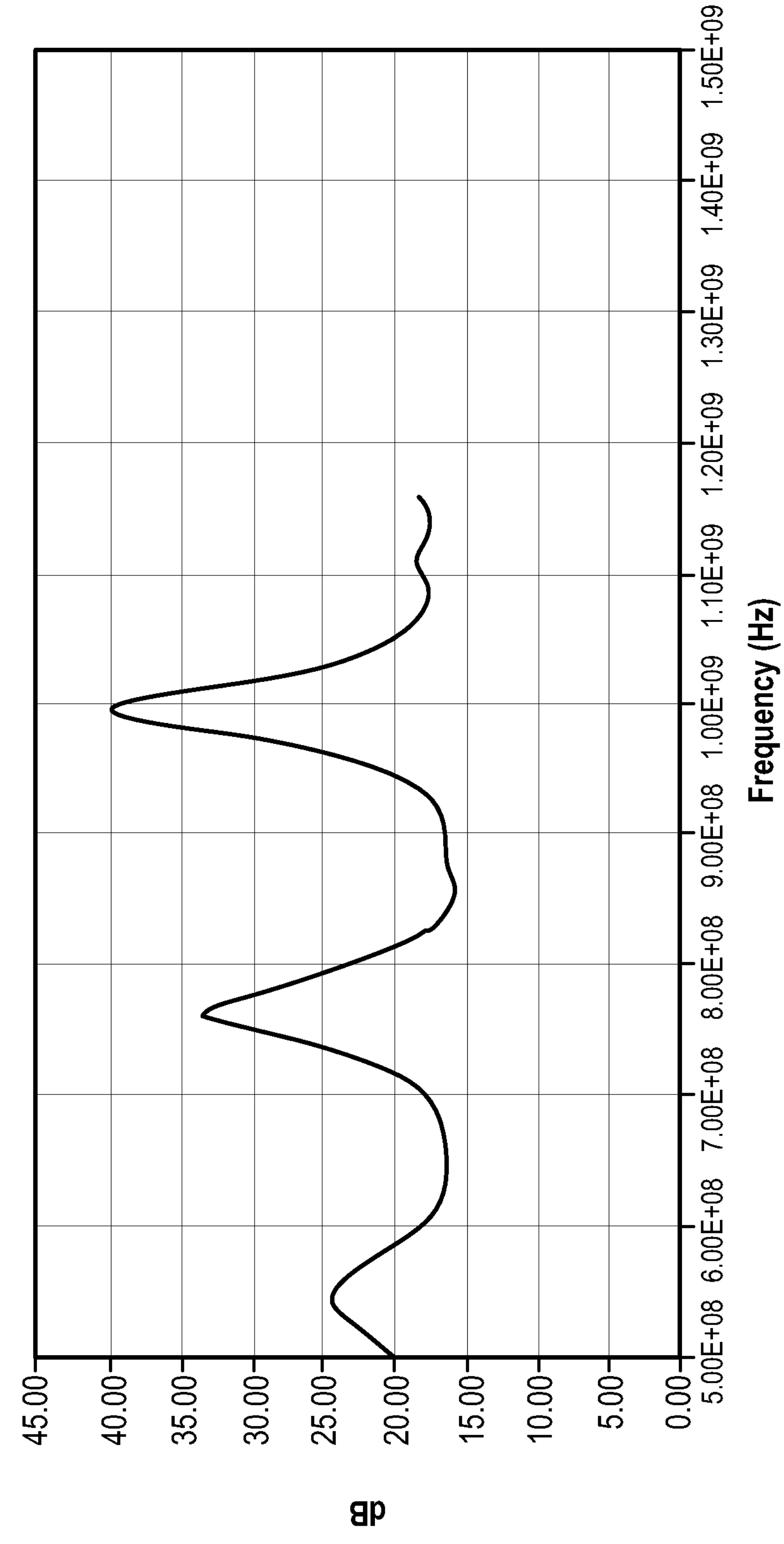

Start
Identify frequency of input signal
S411
Retrieve previously stored gain and phase settings
S412
Set adjustable gain components and phase shifters
S413
Adjust magnitude of second coupled signal
S414
Adjust phase of second coupled signal
S415
Add adjusted second coupled signal and output of third port
S416
Output first coupled signal
S417
Adjust magnitude of first coupled signal
S418
Adjust phase of first coupled signal
S419
Add adjusted first coupled signal and output of fourth port
S420
Output second coupled signal
S421
End

Fig. 4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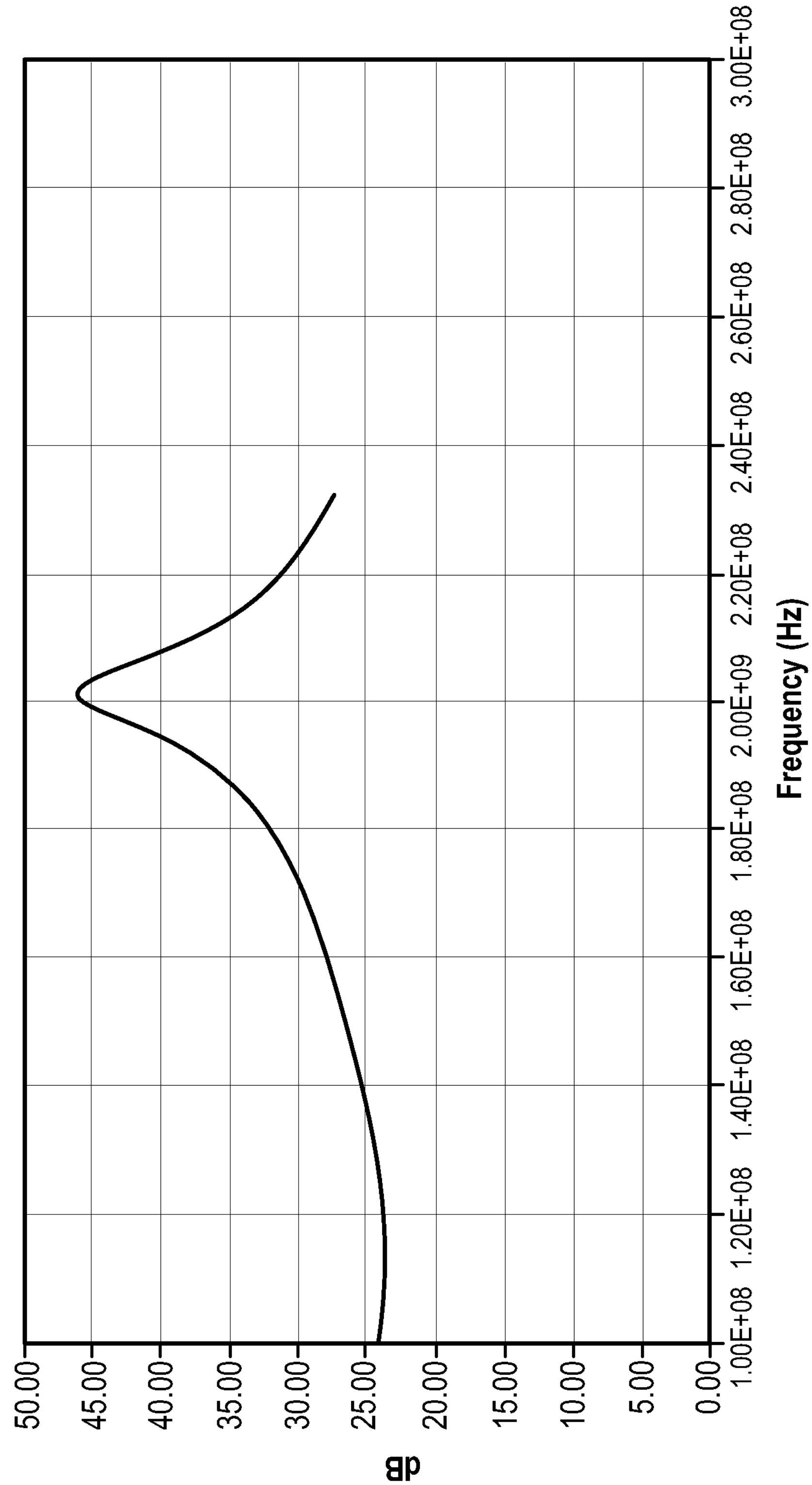
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
5.00E+08
6.00E+08
7.00E+08
8.00E+08
9.00E+08
1.00E+09
1.10E+09
1.20E+09
1.30E+09
1.40E+09
1.50E+09
Frequency (Hz)

Fig. 5A


dB
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45.00
40.00
35.00
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25.00
20.00
15.00
10.00
5.00
0.00
1.00E+08
1.20E+08
1.40E+08
1.60E+08
1.80E+08
2.00E+09
2.20E+08
2.40E+08
2.60E+08
2.80E+08
3.00E+08
Frequency (Hz)

Fig. 5B

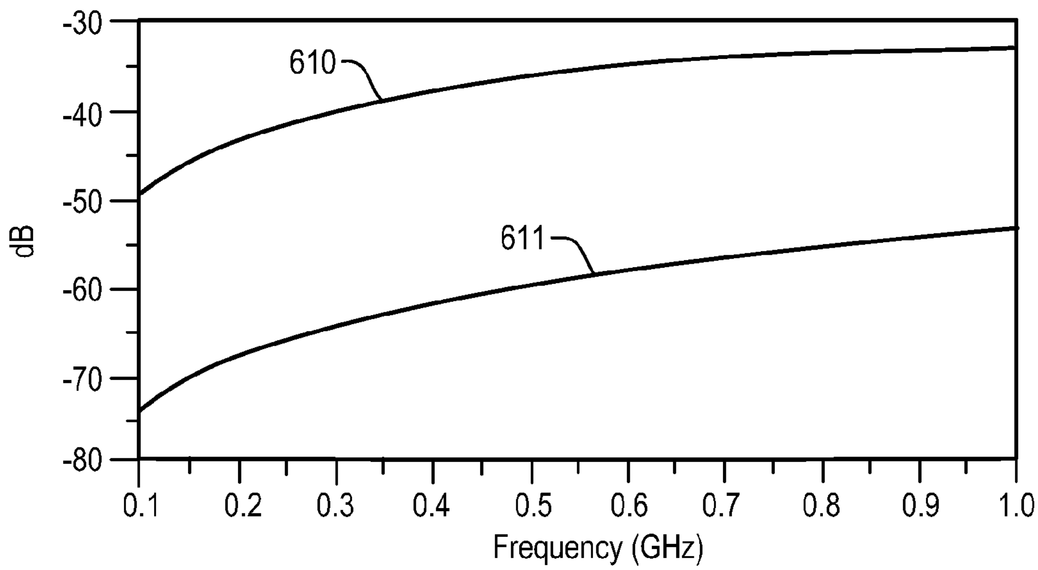
-30
-40
-50
-60
-70
-80
dB
610
611
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Frequency (GHz)

Fig. 6A

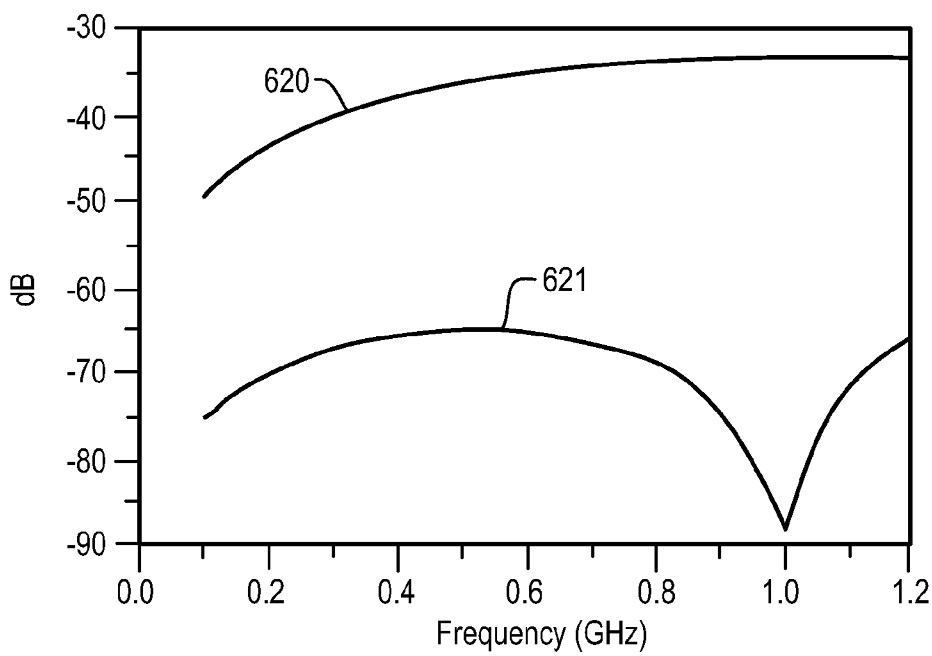
-30
-40
-50
-60
-70
-80
-90
dB
620
621
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Frequency (GHz)

Fig. 6B

ADJUSTABLE DIRECTIONAL COUPLER CIRCUIT

BACKGROUND

A directional coupler is a four-port device that enables measurement of power of an input signal. The four ports may be labeled input port, output port, forward coupled port and the reverse coupled port. The input and output ports connect to a device under test (DUT), for example, and the forward and reverse coupled ports are used for monitoring power. The signal at the forward coupled port is proportional to the signal traveling in a forward direction, from the input port to the output port (e.g., input signal). The signal at the reverse coupled port is proportional to the signal traveling in a reverse direction, from the output port to the input port (e.g., reflected signal).

One common application of a directional coupler is monitoring power between a radio transmitter and an antenna in a radio system, for example, where the transmitter and the antenna are connected to the input port and the output port of the directional coupler, respectively. Power flows from the transmitter to the antenna (forward power), and thus from the input port to the output port. When the antenna is imperfect, some of the power reflects off the antenna (reverse power) and flows back toward the input port, returning to the radio transmitter. This is undesirable for at least two reasons. First, the reverse power reduces the amount of power radiated from the antenna, thus reducing range and sensitivity of the radio system. Second, an excessive amount of the reverse power may damage the transmitter. Therefore, antenna designs attempt to minimize reverse power.

FIG. **1** is a simplified block diagram of a directional coupler. Referring to FIG. **1**, directional coupler **110** includes transmission line **111** having a first port **101** (input port) for receiving an input signal, e.g., from a radio transmitter, and a second port **102** (output port) for outputting the input signal, e.g. to an antenna. The directional coupler **110** also includes coupled line **112** having a third port **103** (forward coupled port) for presenting sampled power of the input signal flowing from the first port **101** to the second port **102**, and a fourth port **104** (reverse coupled port) for presenting sampled power of a reflected signal (reflected from a load connected to the second port **102**) flowing from the second port **102** to the first port **101**. The fourth port **104** may also be referred to as an isolated port with regard to the input signal, and the third port **103** may be referred to as an isolated port with regard to the reflected signal. As mentioned above, the directional coupler **110** has the property that the power of the coupled signal measured at the third port **103** is proportional to the forward power, flowing from the first port **101** to the second port **102**. Similarly, the power of the coupled signal measured at the fourth **104** is proportional to the reverse power, flowing from second port **102** to the first port **101**. Thus, by measuring the power of the coupled signals at the third and fourth ports **103** and **104**, the forward power and reverse power flowing between the transmitter and the antenna may be determined, respectively.

Power traveling between any two ports of the directional coupler **110** may be indicated using S-parameters, as is know in the art, where the first port **101** is port "1," the second port **102** is port "2," the third port **103** is port "3" and the fourth port **104** is port "4." Thus, the ratio between the power at the third port **103** and the forward power of the input signal, which may be referred to as the "coupling factor," may be indicated by S_{31} in S-parameter terminology. In addition, S_{31} is a measure of the sensitivity at the third port **103** to the forward power, and S_{32} is a measure of the sensitivity at the third port **103** to the reverse power. The ratio between S-parameters S_{32} and S_{31} may be referred to as "directivity." Accordingly, the S-parameters of the directional coupler **110** with respect to coupling factor and directivity may be indicated as follows:

$$S_{31}=C$$

$$S_{32}=C*D$$

$$S_{42}=C$$

$$S_{41}=C*D$$

$$S_{12}=S_{21}\approx 1$$

In an ideal directional coupler, the third port **103** outputs only a coupled signal that is proportional to the forward power, and is not affected at all by the reverse power. Likewise, the fourth port **104** ideally outputs only a coupled signal that is proportional to the reverse power, and is not affected at all by the forward power. Of course, no actual directional coupler is ideal, so in practice the third port **103** actually outputs a coupled signal that includes both a desired coupled signal that is proportional to the forward power and an extraneous coupled signal that is proportional to the reverse power, and the fourth port **104** also outputs a coupled signal that includes both a desired coupled signal that is proportional to the reverse power and an extraneous coupled signal that is proportional to the forward power. The extraneous coupled signals negatively affect directivity.

Some conventional directional couplers attempt to limit extraneous coupled signals and improve directivity through manual tuning during production, which is time consuming and inflexible. For example, some conventional directional couplers include tuning blocks that are shifted to achieve desired directivity, and then glued in place. This process is time consuming in that the coupler lid must be removed repeatedly to adjust and readjust the tuning blocks, but replaced each time to measure directivity. Further, once the tuning blocks are set, the directional coupler is effectively limited to the frequency at which the tuning occurred. Similarly, some conventional directional couplers include metal tuning slugs that are threaded through the body of the directional coupler. Since the tuning slugs can be accessed from the outside, the coupler lid does not need to be removed for tuning. However, the manual alignment is still time consuming and cannot be easily readjusted for handling input signals having different frequencies.

Accordingly, there is a need to improve directivity of directional couplers, particularly by reducing or eliminating the effects of reverse power on the output of the third port **103**, as well as by reducing or eliminating the effects of forward power on the output of the forth port **104**. Generally, improving the directivity of a coupler enables more accurate measurements of the forward power and/or reverse power.

SUMMARY

In a representative embodiment, an adjustable directional coupler circuit includes a directional coupler and a correction circuit. The directional coupler includes a first port configured to receive an input signal from a signal source; a second port configured to output the input signal to a load; a third port configured to output a first coupled signal comprising a desired first coupled signal proportional to forward power of the input signal flowing from the first port to the second port and an extraneous first coupled signal proportional to reverse power of a reflected signal flowing from the second port to the

first port, the reflected signal corresponding to a portion of the input signal reflected from the load; and a fourth port configured to output a second coupled signal comprising a desired second coupled signal proportional to the reverse power and an extraneous second coupled signal proportional to the forward power. The correction circuit is configured to adjust magnitude and phase of a sample of the second coupled signal to provide an adjusted second coupled signal, and to sum the adjusted second coupled signal and the first coupled signal to cancel the extraneous first coupled signal.

In another representative embodiment, a correction circuit is provided for a directional coupler comprising an input port configured to receive an input signal, an output port configured to output the input signal to a load, a forward coupled port configured to output a first coupled signal comprising a desired first coupled signal proportional to forward power of the input signal, and a reverse coupled port configured to output a second coupled signal comprising a desired second coupled signal proportional to reverse power of a reflected signal corresponding to a portion of the input signal reflected from the load. The correction circuit includes a first adjustable gain component configured to adjust a magnitude of the second coupled signal output from the reverse coupled port; a first adjustable phase shifter configured to adjust a phase of the second coupled signal to provide an adjusted second coupled signal; and a first summing circuit configured to add the adjusted second coupled signal and the first coupled signal at the forward coupled port in order to cancel an extraneous first coupled signal of the first coupled signal proportional to the reverse power of the reflected signal. The first adjustable gain component and the first adjustable phase shifter are adjustable based on a frequency of the input signal.

In another representative embodiment, a method is provided for cancelling directivity errors of a directional coupler comprising a first port configured to receive an input signal, a second port configured to output the input signal to a load, a third port configured to output a first coupled signal comprising a desired first coupled signal proportional to forward power of the input signal and an extraneous first coupled signal proportional to reverse power of a reflected signal corresponding to a portion of the input signal reflected from the load, and a fourth port configured to output a second coupled signal comprising a desired second coupled signal proportional to the reverse power and an extraneous second coupled signal proportional to the forward power. The method includes identifying a frequency of the input signal, retrieving gain and phase settings corresponding to the identified frequency, adjusting magnitude and phase of the second coupled signal according to the retrieved gain and phase settings, respectively, to provide an adjusted second coupled signal, combining the adjusted second coupled signal and the first coupled signal at the third port to cancel the extraneous first coupled signal, and outputting the desired first coupled signal.

BRIEF DESCRIPTION OF THE DRAWINGS

The illustrative embodiments are best understood from the following detailed description when read with the accompanying drawing figures. It is emphasized that the various features are not necessarily drawn to scale. In fact, the dimensions may be arbitrarily increased or decreased for clarity of discussion. Wherever applicable and practical, like reference numerals refer to like elements.

FIG. **1** is a simplified block diagram of a directional coupler.

FIG. **2** is a simplified block diagram of an adjustable directional coupler circuit, according to a representative embodiment.

FIG. **3** is a simplified circuit diagram of the adjustable directional coupler circuit of FIG. **2**, according to a representative embodiment.

FIG. **4** is a flow diagram showing a method of cancelling directivity errors of a directional coupler, according to a representative embodiment.

FIG. **5**A is a graph depicting directivity of the adjustable directional coupler circuit of FIG. **2**, calibrated for performance at 1 GHz, according to a representative embodiment.

FIG. **5**B is a graph depicting directivity of the adjustable directional coupler circuit of FIG. **2**, calibrated for performance at 200 MHz, according to a representative embodiment.

FIG. **6**A is a graph depicting S-parameters S_{31} and S_{32} indicating directivity of a conventional directional coupler.

FIG. **6**B is a graph depicting S-parameters S_{31} and S_{32} indicating directivity of the adjustable directional coupler circuit of FIG. **2**, according to a representative embodiment.

DETAILED DESCRIPTION

In the following detailed description, for purposes of explanation and not limitation, illustrative embodiments disclosing specific details are set forth in order to provide a thorough understanding of embodiments according to the present teachings. However, it will be apparent to one having had the benefit of the present disclosure that other embodiments according to the present teachings that depart from the specific details disclosed herein remain within the scope of the appended claims. Moreover, descriptions of well-known devices and methods may be omitted so as not to obscure the description of the example embodiments. Such methods and devices are within the scope of the present teachings. Generally, it is understood that the drawings and the various elements depicted therein are not drawn to scale.

According to various embodiments, an adjustable correction circuit is added to the forward and reverse coupled ports of a directional coupler to provide an additional stage of cancellation. Generally, the correction circuit samples the second coupled signal at the reverse coupled port, adjusts its magnitude and phase, and sums it with the first coupled signal output by the forward coupled port (which includes a desired first coupled signal as well as an extraneous first coupled signal). The magnitude and phase adjusted second coupled signal is substantially equal in magnitude and opposite in phase to the extraneous first coupled signal, which is therefore canceled out by a summing operation. In addition, the correction circuit samples the first coupled signal at the forward coupled port, adjusts its magnitude and phase, and sums it with the second coupled signal output by the reverse coupled port (which includes a desired second coupled signal as well as an extraneous second coupled signal). The magnitude and phase adjusted first coupled signal is substantially equal in magnitude and opposite in phase to the extraneous second coupled signal, which is therefore also canceled out by a summing operation.

FIG. **2** is a simplified block diagram of an adjustable directional coupler circuit, according to a representative embodiment.

Referring to FIG. **2**, adjustable directional coupler circuit **200** includes directional coupler **210** and correction circuit **220**. As discussed above, the directional coupler **210** includes transmission line **211** having a first port **201** (input port) for receiving an input signal and a second port **102** (output port) for outputting the input signal. The first port **201** may be connected to a signal source, such as a radio transmitter, to receive the input signal, and the second port **202** may be connected to a load, such as an antenna, for example. Of course the various embodiments are also applicable to various other types of signal sources and/or loads.

The directional coupler **210** also includes coupled line **212** having a third port **203** (forward coupled port) and a fourth port **204** (reverse coupled port). The third port **203** is configured to output a first coupled signal which includes a desired first coupled signal, having power proportional to the forward power of the input signal flowing from the first port **201** to the second port **202**, and an extraneous first coupled signal, having power proportional to the reverse power of the reflected signal flowing from the second port **202** to the first port **201**. The fourth port **204** is configured to output a second coupled signal which includes a desired second coupled signal, having power proportional to the reverse power of the reflected signal flowing from the second port **202** to the first port **201**, and an extraneous second coupled signal, having power proportional to the forward power of the input signal flowing from the first port **201** to the second port **202**. As mentioned above, the reflected signal corresponds to a portion of the input signal reflected from the load connected to the second port **202**. Thus, by measuring the power of the desired first coupled signal and the desired second coupled signal at the third and fourth ports **203** and **204**, respectively, the forward power and the reverse power may be determined.

The correction circuit **220** is configured to reduce or eliminate the extraneous first coupled signal output at the third port **203** and the extraneous second coupled signal output at the fourth port **204**, thereby improving directivity of the directional coupler **210**. The correction circuit **220** generally accomplishes this by substantially cancelling out the extraneous first coupled signal at the third port **203** using a sample of the second coupled signal output at the fourth port **204**, and/or by substantially cancelling out the extraneous second coupled signal at the fourth port **203** using a sample of the first coupled signal output at the third port **203**. Accordingly, the correction circuit **220** provides corrected third port **203'** and/or corrected fourth port **204'**. The corrected third port **203'** outputs the desired first coupled signal with no or minimal extraneous first coupled signal. The corrected fourth port **204'** outputs the desired second coupled signal with no or minimal extraneous second coupled signal.

In the depicted embodiment, the correction circuit **220** includes a first feed forward circuit **221** connected to the corrected third port **203'**, a second feed forward circuit **222** connected to the corrected fourth port **204'**, a memory **240**, and a controller **250**. Notably, in alternative embodiments, the correction circuit **220** may include only one of the first and second feed forward circuits **221** and **222** for reducing or eliminating the corresponding one of the extraneous first and second coupled signals, respectively, without departing from the scope of the present teachings.

The first feed forward circuit **221** is configured to adjust magnitude (amplitude) and phase of a sample of the second coupled signal at the fourth port **204** to provide an adjusted second coupled signal, and to add the adjusted second coupled signal and the first coupled signal at the third port **203** to cancel out all or a portion of the extraneous first coupled signal, leaving the desired first coupled signal. The first feed forward circuit **221** includes first adjustable gain component **223**, first adjustable phase shifter **224** and first summing circuit **225**. The first adjustable gain component **223** is configured to adjust the magnitude of the sample of the second coupled signal received from the fourth port **204** to match the magnitude of the extraneous first coupled signal. The first adjustable gain component **223** may be implemented using a programmable attenuator or variable resistor, for example. The first adjustable phase shifter **224** is configured to adjust the phase of the sample of the second coupled signal received from the first adjustable gain component **223**, e.g., to be in phase or 180 degrees out of phase with the phase of the extraneous first coupled signal (depending on the type of first summing circuit **225**), to provide an adjusted second coupled signal. The first adjustable phase shifter **224** may be implemented using selectable delay lines having different lengths, for example. Of course the order of the first adjustable gain component **223** and the first adjustable phase shifter **224** may be reversed, without departing from the scope of the present teachings.

The adjusted second coupled signal is input to the first summing circuit **225**, which combines the adjusted second coupled signal with the first coupled signal at the third port **203**, substantially canceling the extraneous first coupled signal. Thus, the desired first coupled signal alone is output at the corrected third port **203'**. The first summing circuit **225** may be implemented using a transformer, a resistive combiner or a differential amplifier, for example. The resistive combiner may be a three-resistor combiner that includes a first resistor connected to the first adjustable phase shifter **224** to receive the adjusted second coupled signal, a second resistor connected to the third port **203** to receive the combined first coupled signal and extraneous first coupled signal, and a third resistor connected to the corrected third port **203'** to output the first coupled signal. Each of the first through third resistors may have the same value, for example. Use of a three-resistor combiner would require the second coupled signal to be shifted to 180 degrees out of phase with the extraneous first coupled signal to provide the adjusted second coupled signal. The differential amplifier may include differential input ports connected to the first adjustable phase shifter **224** and the third port **203**, respectively, and an output port connected to the corrected third port **203'** and configured to output a difference between the adjusted second coupled signal and the first coupled signal, thus providing the desired first coupled signal. Notably, use of a differential amplifier would require the second coupled signal to be shifted to 0 degrees out of phase (or, in phase) with the extraneous first coupled signal to provide the adjusted second coupled signal. Of course, other types of summing circuits may be included without departing from the scope of the present teachings.

The magnitude and phase of the extraneous first coupled signal vary according to frequency of the input signal. For example, the correct adjustment amounts of the first adjustable gain component **223** and the first adjustable phase shifter **224** for an input signal at 200 MHz is different than the correct adjustment amounts for an input signal at 1 GHz. Therefore, the amount of gain adjusted by the first adjustable gain component **223** and the amount of phase shifted by the first adjustable phase shifter **224** are set as a function of the frequency of the input signal.

In order to determine the appropriate amounts of gain and phase shifting, the correction circuit **220** is previously calibrated for multiple different input signal frequencies. The gain and phase settings corresponding to each input signal frequency are stored in memory **240**, along with the corresponding input signal frequency, during the calibration phase of the correction circuit **220**. The input signal frequencies for which calibration is performed may be discretionary. For example, a user may wish to cover a broad range of input signal frequencies, and therefore provide gain and phase settings corresponding to input signal frequencies from 25 MHz to 4 GHz at 25 MHz intervals. Of course, other frequency ranges and increments may be included without departing from the scope of the present teachings.

In order to calibrate the gain and phase settings, input signals having the desired frequencies are consecutively applied to the directional coupler circuit **200** (or to a direction coupling circuit having the same characteristics). For each input signal frequency, the first adjustable gain component **223** and the first adjustable phase shifter **224** are adjusted until the extraneous first coupled signal is no longer detected at the output of the third port **203**. The respective gain and phase settings are then stored in the memory **240** in relation to the input signal frequency.

Once the calibrated gain and phase settings and corresponding input signal frequencies are stored in memory **240**, they may be selectively retrieved by the controller **250** and applied to the first adjustable gain component **223** and the first adjustable phase shifter **224** in accordance with the frequency of the input signal. In an embodiment, the frequency of the input signal may be determined manually. For example, the user may set the numeric value of the input signal frequency in the controller **250** using an interface, such as a rotatable knob, a key pad, a touch screen, or the like. In alternative embodiments, the frequency of the input signal may be determined automatically by automated test equipment and/or single detectors, such as a radio receiver, an oscilloscope, a signal analyzer, or the like. Regardless of how the input signal frequency is identified, the controller **250** retrieves the previously stored gain and phase settings corresponding to the input signal frequency from the memory **240** from among multiple previously stored gain and phase settings, and applies the retrieved gain and phase settings to the first adjustable gain component **223** and the first adjustable phase shifter **224**, respectively.

The controller **250** may be implemented, at least in part, using one or more processing devices, such as a processor, a microprocessor, one or more application specific integrated circuits (ASICs), one or more field-programmable gate arrays (FPGAs), or combinations thereof, using software, firmware, hard-wired logic circuits, or combinations thereof. The controller **250** includes an interface for interfacing with the means by which the input signal frequency is identified, discussed above. The memory **240** may include non-transitory, tangible computer readable medium for storing the calibrated gain and phase settings and corresponding frequencies, such as read only memory (ROM), electrically programmable ROM (EPROM), erasable EPROM (EEPROM), flash memory, random access memory (RAM) static RAM (SRAM), dynamic RAM (DRAM), a USB drive, and the like. The memory **240** may be a relational database, for example.

The second feed forward circuit **222** is configured to adjust magnitude and phase of a sample of the first coupled signal at the third port **203** to provide an adjusted first coupled signal, and to add the adjusted first coupled signal and the second coupled signal at the fourth port **204** to cancel out all or a portion of the extraneous second coupled signal, leaving the desired second coupled signal. The second feed forward circuit **222** is implemented in substantially the same manner as the first feed forward circuit **221**, discussed above, except in the opposite direction. That is, the second forward circuit **221** includes second adjustable gain component **226**, second adjustable phase shifter **227** and second summing circuit **228**. The second adjustable gain component **226** is configured to adjust the magnitude of the sample of the first coupled signal received from the third port **203** to match the magnitude of the extraneous second coupled signal. The second adjustable phase shifter **227** is configured to adjust the phase of the sample of the first coupled signal received from the second adjustable gain component **226**, e.g., to be in phase or 180 degrees out of phase with the phase of the extraneous second coupled signal (depending on the type of second summing circuit **228**), to provide an adjusted first coupled signal. Of course the order of the second adjustable gain component **226** and the second adjustable phase shifter **227** may be reversed, without departing from the scope of the present teachings. The adjusted first coupled signal is input to the second summing circuit **228**, which combines the adjusted first coupled signal with the second coupled signal at the fourth port **204**, substantially canceling the extraneous second coupled signal. Thus, the desired second coupled signal alone is output at the corrected fourth port **204'**.

The magnitude and phase of the extraneous second coupled signal vary according to frequency of the input signal. Therefore, the amount of gain adjusted by the second adjustable gain component **226** and the amount of phase shifted by the second adjustable phase shifter **227** are set as a function of the frequency of the input signal. In order to determine the appropriate amounts of gain and phase shifting, the correction circuit **220** may be previously calibrated for multiple different input signal frequencies. The gain and phase settings of the second adjustable gain component **226** and the second adjustable phase shifter **227** corresponding to each desired input signal frequency are stored in memory **240**, along with the corresponding input signal frequency, during the calibration phase of the correction circuit **220**, as discussed above.

FIG. **3** is a simplified circuit diagram of an adjustable directional coupler circuit of FIG. **2**, according to a representative embodiment. More particularly, FIG. **3** shows only an embodiment of a first feed forward circuit connected between the fourth port and the third port and a second feed forward circuit connected between the third port and the fourth port, which may be implemented in substantially the same manner, except in the opposite direction, as mentioned above.

Referring to FIG. **3**, adjustable directional coupler circuit **300** includes directional coupler **310** and correction circuit **320**, which are illustrative implementations of the directional coupler **210** and the correction circuit **220**, discussed above. The directional coupler **310** includes transmission line **311** having a first port **301** (input port) for receiving an input signal from signal source **305** (e.g., transmitter) and a second port **302** (output port) for outputting the input signal to load **306** (e.g., antenna). For purposes of illustration, it may be assumed that the input signal has a frequency of about 1 GHz.

The directional coupler **310** also includes coupled line **312** having a third port **303** (forward coupled port) and a fourth port **304** (reverse coupled port). The third port **303** is configured to output a first coupled signal, which includes a desired first coupled signal having power proportional to the forward power of the input signal and an extraneous first coupled signal having power proportional to the reverse power of the reflected signal. The fourth port **304** is configured to output a second coupled signal, which includes a desired second coupled signal having power proportional to the reverse power of the reflected signal and an extraneous second coupled signal having power proportional to the forward power of the input signal.

The correction circuit **320** is configured to reduce or eliminate the extraneous first coupled signal output at the third port **303** and the extraneous second coupled signal output at the fourth port **304**, thereby improving directivity of the directional coupler **310**. In particular, first feed forward circuit **321** is configured to substantially cancel out the extraneous first coupled signal at the third port **303** using a sample of the second coupled signal output at the fourth port **304**, and second feed forward circuit **322** is configured to substantially cancel out the extraneous second coupled signal at the fourth port **304** using a sample of the first coupled signal output at the third port **303**.

In the depicted embodiment, the first feed forward circuit **321** is connected to the third port **303**, the fourth port **304** and corrected third port **303'**, as well as to the memory **240** and the controller **250** (not shown in FIG. **3**), which enable adjusting magnitude and phase of a sample of the second coupled signal at the fourth port **304** to provide an adjusted second coupled signal, discussed below. The first feed forward circuit **321** includes programmable attenuator **323**, delay line selector **324** and three-resistor combiner **325**. The three-resistor combiner **325** includes input resistor **351** connected to the delay line selector **324**, input resistor **352** connected to the third port **303**, and output resistor **353** connected to the corrected third port **303'**. The value of each of the input resistor **351**, the input resistor **352** and the output resistor **353** may be about 16.7 ohms, for example.

The programmable attenuator **323** is configured to adjust the magnitude of a sample of the second coupled signal received from the fourth port **304** to match the magnitude of the extraneous first coupled signal at the third port **303**. The level of attenuation (or resistance) of the programmable attenuator **323** may be set by the controller **250**, which retrieves the setting corresponding to the 1 GHz input signal frequency from the memory **240**. The delay line selector **324** is configured to adjust the phase of the sample of the second coupled signal received from the programmable attenuator **323** to be 180 degrees out of phase with the phase of the extraneous first coupled signal to provide an adjusted second coupled signal. The phase is adjusted by selecting the one of multiple delay lines having different lengths that corresponds to the 1 GHz input signal frequency. In the depicted embodiment, the delay line selector **324** includes two representative delay lines, one of which corresponds to the 1 GHz input signal frequency and the other of which corresponds to a 200 MHz inputs signal frequency. Of course, the delay line selector **324** may include alternative and/or additional delay lines corresponding to different input signal frequencies, without departing from the scope of the present teachings. The selection is made by the controller **250**, which retrieves the delay line setting corresponding to the 1 GHz input signal frequency from the memory **240**. Also, as mentioned above, the order of the programmable attenuator **323** and the delay line selector **324** may be reversed, without departing from the scope of the present teachings.

The adjusted second coupled signal output by the delay line selector **324** is provided to one input of the three-resistor combiner **325** (at the input resistor **351**), and the first coupled signal output by the third port **303** (including the desired first coupled signal and the extraneous first coupled signal) is provided to the other input of the three-resistor combiner **325** (at the input resistor **352**). As a result, the three-resistor combiner **325** substantially cancels the extraneous first coupled signal by combining the input signals, and outputs (at the output resistor **353**) only the desired first coupled signal to the corrected third port **303'**. Impedance of the corrected third port **303'** is represented by resistor **307**, which may be about 50 ohms, for example.

Also in the depicted embodiment, the second feed forward circuit **322** is connected to the fourth port **304**, the third port **303** and corrected fourth port **304'**, as well as to the memory **240** and the controller **250** (not shown in FIG. **3**), which enable adjusting magnitude and phase of a sample of the first coupled signal at the third port **303** to provide an adjusted first coupled signal, discussed below. Similar to the first feed forward circuit **321**, the second feed forward circuit **322** includes programmable attenuator **343**, delay line selector **344** and three-resistor combiner **345**. The three-resistor combiner **345** includes input resistor **371** connected to the delay line selector **344**, input resistor **372** connected to the fourth port **304**, and output resistor **373** connected to the corrected fourth port **304'**. The value of each of the input resistor **371**, the input resistor **372** and the output resistor **373** may be about 16.7 ohms, for example.

The programmable attenuator **343** is configured to adjust the magnitude of a sample of the first coupled signal received from the third port **303** to match the magnitude of the extraneous second coupled signal at the forth port **304**. The level of attenuation (or resistance) of the programmable attenuator **343** may be set by the controller **250**, as discussed above. The delay line selector **344** is configured to adjust the phase of the sample of the first coupled signal received from the programmable attenuator **343** to be 180 degrees out of phase with the phase of the extraneous second coupled signal to provide an adjusted first coupled signal. The phase is adjusted under control of the controller **250** as discussed above. The order of the programmable attenuator **343** and the delay line selector **344** may be reversed, without departing from the scope of the present teachings.

The adjusted first coupled signal output by the delay line selector **344** is provided to one input of the three-resistor combiner **345** (at the input resistor **371**), and the second coupled signal output by the fourth port **304** (including the desired second coupled signal and the extraneous second coupled signal) is provided to the other input of the three-resistor combiner **345** (at the input resistor **372**). As a result, the three-resistor combiner **345** substantially cancels the extraneous second coupled signal by combining the input signals, and outputs (at the output resistor **373**) only the desired second coupled signal to the corrected fourth port **304'**. Impedance of the corrected third port **304'** is represented by resistor **308**, which may be about 50 ohms, for example.

FIG. **4** is a flow diagram showing a method of canceling directivity errors of a directional coupler, according to a representative embodiment.

As discussed above, the directional coupler includes a first port (input port) configured to receive an input signal, a second port (transmit port) configured to output the input signal to a load, a third port (forward coupled port) configured to output a first coupled signal including a desired first coupled signal proportional to forward power of the input signal and an extraneous first coupled signal proportional to reverse power of a reflected signal corresponding to a portion of the input signal reflected from the load, and a fourth port (reverse coupled port) configured to output a second coupled signal including a desired second coupled signal proportional to the reverse power an extraneous second coupled signal proportional to the forward power. The method of canceling directivity errors of the directional coupler substantially cancels out the extraneous first coupled signal from the output of the third port and the extraneous second coupled signal from output of the fourth port using a correction circuit (e.g., correction circuit **220**).

Referring to FIG. **4**, frequency of the input signal is identified in block **S411**. For example, the frequency of the input signal may be provided to the controller **250** by a user via an interface, such as a rotatable knob, a key pad, a touch screen, or the like, or the frequency may be determined and provided by automated test equipment and/or single detector. In block **S412**, previously stored gain and phase settings corresponding to the input signal frequency identified in block **S411** are retrieved from memory. For example, the controller **250** may retrieve the previously stored gain and phase settings from the memory **240** using a look-up table or other retrieval tool. The gain and phase settings are determined during an initial calibration process, during which the gain and phase settings may be empirically determined, for example, by applying input signals having various predetermined frequencies to the directional coupler and adjusting the gain and phase settings until the extraneous first and second coupled signals are canceled from the outputs of the third and fourth ports, respectively. The determined gain and phase settings may then be stored in the memory **240** for future use. In block S**413**, the retrieved gain and phase settings are used to set adjustable gain components (e.g., first and second adjustable gain components **223**, **226**) and adjustable phase shifters (e.g., first and second adjustable phase shifters **224**, **227**).

Notably, blocks S**414** to S**417** in FIG. **4** are directed to canceling the extraneous first coupled signal from the output of the third port **203**, leaving the desired first coupled signal. Similarly, blocks S**418** to S**421** are directed to canceling the extraneous second coupled signal from the output of the fourth port **203**, leaving the desired second coupled signal. The order of steps shown in FIG. **4** is not intended to be limiting. Rather, all or part of blocks S**414** to S**417** may be performed before or after all or part of blocks S**418** to S**421** are performed, or all or a portion of blocks S**414** to S**417** blocks may be performed at substantially the same time as all or a portion of blocks S**418** to S**421**, without departing from the scope of the present teachings. Also, in alternative embodiments, the correction circuit may be configured to cancel only one of the extraneous first coupled signal or the extraneous second coupled signal, in which case only blocks S**414** to S**417** or blocks S**418** to S**421** would be performed. Cancelation of both is discussed herein for purposes of illustration.

In block S**414**, the magnitude of a sample of the second coupled signal from the fourth port is adjusted by the set first adjustable gain component **223** to match the magnitude of the extraneous first coupled signal. In block S**415**, the phase of the sample of the second coupled signal is adjusted by the set first adjustable phase shifter **224** to provide an adjusted second coupled signal that has a desired phase relationship (e.g., in phase or 180 degrees out of phase) with the extraneous first coupled signal. In block S**416**, the adjusted second coupled signal is added to the first coupled signal at the third port **203**, such that the adjusted second coupled signal substantially cancels the extraneous first coupled signal in the first coupled signal, leaving the desired first coupled signal, which is output in block S**417**.

Similarly, the magnitude of a sample of the first coupled signal from the third port is adjusted by the set adjustable gain component **226** in block S**418** to match the magnitude of the extraneous second coupled signal. In block S**419**, the phase of the sample of the first coupled signal is adjusted by the set adjustable phase shifter **227** to provide an adjusted first coupled signal that has a desired phase relationship (e.g., in phase or 180 degrees out of phase) with the extraneous second coupled signal. In block S**420**, the adjusted first coupled signal is added to the output of the fourth port **204**, such that the adjusted first coupled signal substantially cancels the extraneous second coupled signal in the second coupled signal, leaving the desired second coupled signal, which is output in block S**421**.

All or a portion of the various operations discussed above with reference to FIG. **4** may be included in logic executable by a computer processor or other processing device, such as the controller **250**, discussed above, and/or some combination of processing devices (e.g., by distributed processing). The operations may be implemented using internal logic or software, stored on a computer readable medium, examples of which are discussed above, and executable by one or more computer processors, ASICs, FPGAs or combinations thereof.

FIG. **5**A is a graph depicting directivity versus frequency of the adjustable directional coupler circuit of FIG. **2** tuned to 1 GHz, according to a representative embodiment. As shown, the directional coupler circuit **200** achieves a directivity of about 40 dB at 1 GHz. In this case, the directional coupler **210** would be considered a high frequency directional coupler. FIG. **5**B is a graph depicting directivity versus frequency of the adjustable directional coupler circuit of FIG. **2** tuned to 200 MHz, according to a representative embodiment. As shown, the directional coupler circuit **200** achieves a directivity of about 46 dB at 200 MHz. In this case, the directional coupler **210** would be considered a low frequency directional coupler. The directional coupler **210** thus exhibits good directivity (e.g., better than −30 dB and even better than −40 dB) over a broad frequency range (e.g., 200 MHz to 1 GHz).

FIG. **6**A is a graph depicting S-parameters S_{31} and S_{32} indicating directivity of a conventional directional coupler, for purposes of comparison. FIG. **6**B is a graph depicting S-parameters S_{31} and S_{32} indicating directivity of the adjustable directional coupler circuit of FIG. **2**, according to a representative embodiment.

Directivity is effectively the difference between S_{32} and S_{31}. Referring to FIG. **6**A, curve **610** shows S-parameter S_{31} and curve **611** shows S-parameter S_{32}. At an input signal frequency of 1 GHz, S_{31} is measured at approximately −33 dB and S_{32} is measured at approximately −53 dB. Therefore, the conventional directional coupler tuned for 1 GHz has directivity of about 20 dB. In comparison, referring to FIG. **6**B, curve **620** shows S-parameter S_{31} and curve **621** shows S-parameter S_{32}. At an input signal frequency of 1 GHz, S_{31} is measured at approximately −33 dB and S_{32} is measured at approximately −88 dB. Therefore, the directional coupler circuit tuned for 1 GHz according to a representative embodiment has directivity of about 55 dB.

According to various embodiments, an adjustable correction circuit can be added to any directional coupler to improve its directivity. The adjustable correction circuit eliminates extraneous first and second coupled signals from the forward and reverse coupled ports, respectively, and enables easy adjustments to components for flexible application over a broad range of input signal frequencies. This enables better directivity over a broad range of input signal frequencies than could be achieved by simply by attempting to manually tune a conventional coupler. For example, conventional couplers generally have less than 25 dB of directivity between 25 MHz and 1000 MHz. The various embodiments discussed herein are able to achieve 40 dB of directivity or more over this same range. In addition, because the adjustable correction circuit may be connected to outputs of any directional coupler (e.g., forward and reverse coupled ports), excellent directivity may be achieved even if the directional coupler otherwise has mediocre directivity. Also, since the adjustable correction circuit is computer/processing circuit controlled (e.g., by controller **250**), alignment may be accomplished automatically with a computer and automated test equipment.

While the disclosure references exemplary embodiments, it will be apparent to those skilled in the art that various changes and modifications may be made without departing from the spirit and scope of the present teachings. Therefore, it should be understood that the above embodiments are not limiting, but illustrative.

What is claimed:

1. An adjustable directional coupler circuit, comprising:

a directional coupler comprising:

a first port configured to receive an input signal from a signal source;

a second port configured to output the input signal to a load;

a third port configured to output a first coupled signal comprising a desired first coupled signal proportional to forward power of the input signal flowing from the first port to the second port and an extraneous first coupled signal proportional to reverse power of a reflected signal flowing from the second port to the first port, the reflected signal corresponding to a portion of the input signal reflected from the load; and

a fourth port configured to output a second coupled signal comprising, a desired second coupled signal proportional to the reverse power and an extraneous second coupled signal proportional to the forward power; and

a correction circuit comprising an adjustable gain component configured to adjust a magnitude of a sample of the second coupled signal, and an adjustable phase shifter configured to adjust a phase of the sample of the second coupled signal, the correction circuit being configured to adjust the magnitude and phase of the sample of the second coupled signal to provide an adjusted second coupled signal, and to sum the adjusted second coupled signal and the first coupled signal at the third port to cancel the extraneous first coupled signal.

2. The adjustable directional coupler circuit of claim 1, wherein the correction circuit is further configured to adjust magnitude and phase of a sample of the first coupled signal to provide an adjusted first coupled signal, and to sum the adjusted first coupled signal and the second coupled signal at the fourth port to cancel out the extraneous second coupled signal.

3. The adjustable directional coupler circuit of claim 1, wherein the signal source comprises a radio transmitter, and the load comprises an antenna.

4. The adjustable directional coupler circuit of claim 1, wherein the magnitude and the phase are adjusted as a function of frequency of the input signal.

5. The adjustable directional coupler circuit of claim 4, wherein adjustment amounts for adjusting the magnitude and the phase, respectively, are previously set for each of a plurality of frequencies of the input signal by calibrating the settings at the plurality of frequencies.

6. The adjustable directional coupler circuit of claim 5, further comprising:

a memory for storing the adjustment amounts corresponding to the calibrated settings; and

a controller configured to retrieve the adjustment amounts from the memory based on the frequency of the input signal and to control the adjustment of the magnitude and the phase according to the adjustment amounts.

7. A correction circuit for a directional coupler comprising an input port configured to receive an input signal, an output port configured to output the input signal to a load, a forward coupled port configured to output a first coupled signal comprising a desired first coupled signal proportional to forward power of the input signal and an extraneous first coupled signal proportional to reverse power of a reflected signal corresponding to a portion of the input signal reflected from the load, and a reverse coupled port configured to output a second coupled signal comprising a desired second coupled signal proportional to the reverse power of the reflected signal, the correction circuit comprising:

a first adjustable gain component configured to adjust a magnitude of the second coupled signal output from the reverse coupled port;

a first adjustable phase shifter configured to adjust a phase of the second coupled signal to provide an adjusted second coupled signal; and

a first summing circuit configured to add the adjusted second coupled signal and the first coupled signal at the forward coupled port in order to cancel the extraneous first coupled signal,

wherein the first adjustable gain component and the first adjustable phase shifter are adjustable in response to a frequency of the input signal.

8. The correction circuit of claim 7, further comprising:

a second adjustable gain component configured to adjust a magnitude of the first coupled signal output from the forward coupled port;

a second adjustable phase shifter configured to adjust a phase of the first coupled signal to provide an adjusted first coupled signal; and

a second summing circuit configured to add the adjusted first coupled signal and the second coupled signal at the reverse coupled port, the second coupled signal further comprising an extraneous second coupled signal proportional to the forward power of the input signal, in order to cancel the extraneous second coupled signal.

9. The correction circuit of claim 7, wherein the first adjustable gain component comprises a programmable attenuator.

10. The correction circuit of claim 7, wherein the first summing circuit comprises a resistive combiner.

11. The correction circuit of claim 7, wherein the first summing circuit comprises a differential amplifier configured to output a difference between the adjusted second coupled signal and the first coupled signal.

12. The correction circuit of claim 7, wherein the first summing circuit comprises a transformer.

13. The correction circuit of claim 7, wherein the first adjustable phase shifter is configured to adjust the phase of the second coupled signal so that the second coupled signal is 180 degrees out of phase with the extraneous first coupled signal at the forward coupled port.

14. The correction circuit of claim 13, wherein the first adjustable gain component is configured to adjust the magnitude of the second coupled signal so that the adjusted second coupled signal has a magnitude that is substantially the same as a magnitude of the extraneous first coupled signal at the forward coupled port.

15. An adjustable directional coupler, comprising:

a first port configured to receive an input signal from a signal source;

a second port configured to output the input signal to a load;

a third port configured to output a first coupled signal comprising a desired first coupled signal proportional to forward power of the input signal flowing from the first port to the second port and an extraneous first coupled signal proportional to reverse power of a reflected signal flowing from the second port to the first port, the reflected signal corresponding to a portion of the input signal reflected from the load; and

a fourth port configured to output a second coupled signal comprising a desired second coupled signal proportional to the reverse power and an extraneous second coupled signal proportional to the forward power; and

a correction circuit configured to adjust magnitude and phase of a sample of the second coupled signal to provide an adjusted second coupled signal, and to sum the adjusted second coupled signal and the first coupled signal at the third port to cancel the extraneous first coupled signal, wherein the magnitude and the phase are adjusted as a function of frequency of the input signal, and adjustment amounts for adjusting the magnitude and the phase, respectively, are previously set for each of a plurality of frequencies of the input signal by calibrating the settings at the plurality of frequencies.

16. The adjustable directional coupler circuit of claim **15**, further comprising:

a memory for storing the adjustment amounts corresponding to the calibrated settings; and

a controller configured to retrieve the adjustment amounts from the memory based on the frequency of the input signal and to control the adjustment of the magnitude and the phase according to the adjustment amounts.

17. The adjustable directional coupler circuit of claim **15**, wherein the signal source comprises a radio transmitter, and the load comprises an antenna.

18. The adjustable directional coupler circuit of claim **15**, wherein the correction circuit is further configured to adjust magnitude and phase of a sample of the first coupled signal to provide an adjusted first coupled signal, and to sum the adjusted first coupled signal and the second coupled signal at the fourth port to cancel out the extraneous second coupled signal.

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